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Review Article

Conservation planning for riverine biodiversity under changing climate: use of models

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Abstract

Floodplain habitat area and quality have decreased significantly over the last decades, mainly due to anthropogenic changes. Conservation efforts targeting floodplain species must consider changing climate when choosing suitable areas for restoration, especially for sessile organisms. Species distribution models, based on data from national and international databases on species' occurrences and various environmental predictors, allow forecasting changes in species' spatial distributions and facilitate planning at the catchment scale. Modelled predictions for floodplain organisms and communities suggest that current protected floodplains in Switzerland do not provide sufficient habitat and refugia for typical floodplain species and that climate-adapted conservation planning is needed which includes new areas. Similarly, visualisations of habitat which might potentially be occupied in the future can help to distinguish refugia from short-term sanctuaries. Temporal changes in water availability, for example, during periods of droughts, are likely to further lead to local habitat decrease of floodplain plant communities, as can be shown in hydrological models at reach scale for the Rhine in Germany. In fragmented landscapes along rivers, protected areas can provide refuge for specialised terrestrial species and promote species conservation, as we report for a floodplain which was protected for 30 years. Future restoration projects at the reach scale should, therefore, include planning at the catchment level, as well as consider hydrological regimes at the reach scale, especially for sessile floodplain species' conservation under changing climate.

Highlights

- Floodplain communities are threatened, especially sessile species;
- Climate-driven species distribution models distinguish refugia and sanctuaries;
- Hydrological predictions under changing climate show shifts of habitat for riverine plants at the local scale;
- A case study from a protected area shows that it promotes floodplain biodiversity;
- Prioritisation of local restoration projects should be based on planning at the catchment scale.

Key words: Catchment scale, floodplain communities, hydrological models, protected areas, refugia, species distribution models

Introduction

Riverine floodplains are hotspots of species (Naiman et al. 2005), harbour distinct plant communities (Sabo et al. 2005) and provide habitat for many sessile organisms like fungi (Jüriado et al. 2009; Mihal and Blanar 2014). While many riverine floodplains are fragmented due to anthropogenic changes (Thoms et al. 2005), the loss of wetlands is accelerated under climate change scenarios (Seavy et al. 2009; Mosner et al. 2015), highlighting the importance of floodplain areas as targets for conservation management and planning (Pullin et al. 2009; Zhang et al. 2023; Kaden et al. 2026).

Changing climate has multiple impacts on terrestrial riverine floodplain biodiversity: driven by changing precipitation patterns and rising temperatures, reduced frequency of annual returning or mid-sized high discharge events and longer drought periods disrupt hydrological connectivity and nutrient cycling, leading to habitat and species loss (Bashinskiy et al. 2024). These changes particularly affect both terrestrial and aquatic species which are dependent on seasonal inundation for reproduction and survival, for example, specialised floodplain plant communities (Gu et al. 2025). Moreover, the joint effects of past anthropogenic changes preventing connectivity of floodplains and long drought periods due to changing climate are particularly disruptive for floodplain functions (e.g. for the river Elbe in Germany, see in Harris et al. 2020 and Coder et al. 2025).

In addition to droughts, climate change promotes also the frequency and severity of extreme flood events (Xiong and Yang 2024), leading to changes in river morphology and impacting floodplain ecosystems more frequently (Death et al. 2015). While floodplain species are adapted to periodic inundation, extreme floods lead to local extinction, displacement and potential long-term shifts in community composition, particularly amongst sessile and less mobile taxa (e.g. plants, Kramer et al. 2008; or macrozoobenthos, Chanut et al. 2019). Nevertheless, extreme floods can temporarily restore connectivity between floodplains and river channels (Wenskus et al. 2025), facilitating long distance dispersal and colonisation of new habitats (Wöllner et al. 2021). To profit from the potential of extreme flood events as rejuvenators of floodplain ecosystems, protected source populations in refugia (ensuring long-term survival) or sanctuaries (short-term survival of species during extreme events), for example, in protected areas and longitudinal connectivity are required and need to be considered in long-term planning for floodplain biodiversity conservation.

One focus of long-term planning for floodplains is on protected areas: given that they are usually ecosystems of high quality, they provide habitat for many species simultaneously. As part of networks of habitats and therein populations (in the case of species forming metapopulations), protected areas also show the potential to serve as refugia and sanctuaries for sessile species' survival during disturbances at various temporal scales and providing source areas for recolonisation of ecosystems after extreme events (Li et al. 2006; Turrini and Giovannetti 2012; Haight and Hammill 2020). This is especially important

for sessile organisms, for which means of dispersal are more limited, despite adaptations to vegetative and long-distance dispersal by propagules or spores (Sarneel 2013). As conservation planning for vulnerable species and habitats within floodplain ecosystems is recommended to focus on the landscape scale (Capon et al. 2013; Kmetova-Biro et al. 2026; Stoffers et al. 2026), indirect methods to assess the habitat availability for species and their potential distribution are needed, as field studies at patch size are too limited to cover spatially extensive areas and field studies at the catchment scale are not feasible to achieve.

In this article, we report three studies of two European countries where different types of models were applied to understand the effect of changing climate on floodplain biodiversity: first, we used species distribution models at the Swiss national scale to analyse if current protected areas provide sufficient areas with ideal environmental conditions for the conservation of floodplain fungi. Second, we describe how dispersal, coupled species distribution models under different climate change scenarios, allow us to distinguish areas which are suitable for long term refugia compared to areas which are only short-term sanctuaries for plant species of Swiss floodplain plant communities. Third, we report how hydrological models at the patch scale in Germany allow for more detailed predictions of changes in habitat availability under drought conditions. The theoretical models are contrasted with a case study of a protected area in Switzerland, reporting a biodiversity increase after 30 years of floodplain protection. Based on the studies reported, we summarise recommendations for conservation planning beneficial for floodplain biodiversity at the catchment scale.

Species distribution modelling

Species distribution models, a type of ecological niche models, allow us to link scattered data on species presence (e.g. citizen-science data) or presence-absence (e.g. from research projects) to be combined in a projected map showing the availability of habitat (Fourcade et al. 2014). They are based on biodiversity data, which can be obtained from international (e.g. www.gbif.org/) or national (e.g. Switzerland: www.infospecies.ch, Germany for plants: www.floraweb.de), monitoring programmes or from field studies. For organism groups for which national field campaigns are carried out to evaluate the Red List status (ideally following the criteria of The International Union for Conservarion of Nature (IUCN) Red List of Threatened Species), the detailed presence and absence data at the national level provide a solid basis for modelling.

Species distribution models require a set of predictors (environmental variables) to delineate the importance of, for example, topographic and geological factors, which are generally available. Climatic projections for various emission scenarios (IPCC 2021) are available at an international scale (www.cordex.org) with a special platform for downscaled European data (www.euro-cordex.net). Depending on the organism or species studied, different predictors might apply: for fungi, our model revealed that the average annual temperature and precipitation are the main factors to model the potential distribution, while for plants, temperature during the growing season and terrain slope (as a proxy for incoming radiation) are crucial factors in our models, similar to findings of studies from other countries (e.g. for plants, see in Huang et al. 2024; for fungi, see in Wollan et al. 2008).

Species distribution models provide the opportunity to understand the main drivers of the presence of habitats and species, under past, current and future environmental conditions (Cassini 2011; Franklin 2013). Based on existing species records, the modelling principle is as follows: first the main ecological conditions for the presence of a given species are identified in a correlative approach, followed by a projection in space and time resulting in a predicted species distribution (Elith and Leathwick 2009). Many species distribution modelling algorithms are available as open source packages in the free software environment R (https://cran.r-project.org) and books with detailed information are available (Guisan et al. 2017; Ovaskainen and Abrego 2020).

Models for the conservation of floodplain fungi

Despite their important role for ecosystem functions, floodplain fungi have not been considered in conservation planning in European directives or national strategies yet. Using various environmental factors to understand community composition of fungi, for example, inferred by genetic methods is considered a suitable approach for conservation planning at various levels (Janowski and Leski 2023). A first attempt to use species distribution models to project the presence of various floodplain fungi was performed with the goal to understand if floodplain conservation planning in Switzerland is beneficial for this previously neglected organism group (Fink et al. 2021). The study revealed that there were more suitable habitat outside currently protected areas than inside these areas for typical fungal species (Fig. 1, see also Fink et al. 2021). This finding is even more important as a majority of species (73%) have been recorded more often inside protected areas than outside in Switzerland (Fink et al. 2021). This stresses the importance of planning and implementing new floodplain fungal reserves within Switzerland even if climate change would not occur.

Fungi are predicted to undergo changes in species composition and geographic distribution due to climate becoming warmer and drier, both worldwide (Qin et al. 2023; Zheng et al. 2023) and in Europe (Morera et al. 2022; Yu et al. 2023) and fungi are also sensitive to changes in water temperatures in floodplain areas (Miura and Urabe 2015).

Models for the conservation of floodplain plant communities

Including climatic predictors is crucial for ecological niche models for long term species conservation: the models using future data allow to predict areas with high probability for persistent suitable habitats and allow planning for protected areas with refugial function (Li et al. 2006; Mi et al. 2023). Projections, based on climatic, geological and topographic factors, have shown that, under future conditions, the protected areas in Switzerland are less suitable for floodplain plant communities (see in Fink and Scheidegger 2021; Fink and Scheidegger 2023). The protected areas are, therefore, not suitable as refugia, but are still sanctuary for temporary survival in the future (Fink and Scheidegger 2021). The projections provide a visualisation of target areas for long-term species preservation, where species find suitable habitat despite changing conditions (Fig. 2).

Figure 1. Projected geographical distribution of *Morchella semilibera* (right), based on an ecological niche model for floodplain macrofungi in Switzerland. While more records (black dots) were present in currently protected areas (outlined in brown), this typical floodplain species is predicted to be more frequent outside protected areas (green) compared to predicted absences (white) along various rivers of the Aare catchment (waterways in blue) in the Central plateau of Switzerland. Figure based on Fink et al. (2021), photo: Andrin Gross.

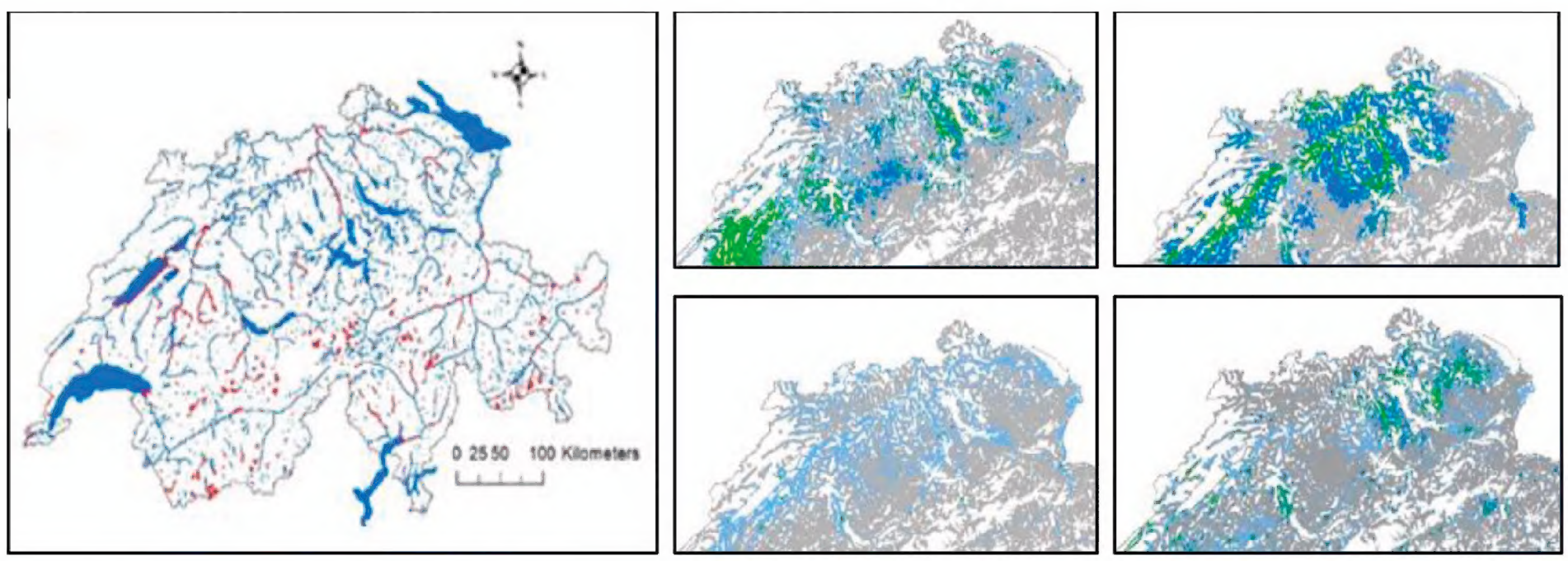

Figure 2. Swiss Floodplains of National importance (left panel, red) along waterbodies (left panel, blue) and visualisation of predicted change in spatial distribution on the Swiss Central plateau with the River Rhine catchment (four panels middle and right) for two floodplain species of the Fraxinion (middle above: *Carex pendula*, middle below: *Ulmus laevis*) and two of the Salicion albae (right above: *Populus nigra*, right below: *Salix myrsinifolia*) plant communities. Persistent habitat with refugia function is indicated in green, while habitat loss (light blue) and habitat gain (dark blue) under moderate climate change scenarios is shown. Grey areas indicate no predicted species presence under current and future temperature and precipitation regimes.

Similar results of changes in distribution patterns for floodplain plants have been found worldwide (Zhang et al. 2023), also using river-specific predictors (Rogers et al. 2020). Models also predict that many invasive plant species are likely to establish in floodplain ecosystems (Pabst et al. 2022) and stress the importance of using dispersal coupled models as in Fink and Scheidegger (2018), given that the effect of dispersal traits on ecological model accuracy is debated (Menuz et al. 2015)

Hydrological models improve predictions for floodplain plants

Species distribution modelling is applicable in conservation planning (Guisan et al. 2013), but, similar to other statistical procedures, the choice of modelling algorithms and accuracy of species data and ecological predictors are key (Franklin 2013). Especially for floodplain ecosystems with high habitat heterogeneity, microclimate might be of utmost importance (Hannah et al. 2014). Similarly, given the interplay between aquatic, amphibious and terrestrial habitats, the hydrological regime in riverine floodplains is an important factor for plant establishment (van Rooijen et al. 2023) and sediment transport also has an effect on the occurrence and distribution floodplain species (Seok et al. 2023). These factors inferred from hydrodynamic models might lead to more precise model predictions (Nylén et al. 2019), but are usually modelled at the patch scale for higher precision, making forecasts for the future more challenging. Therefore, hydrological projections under changing climate at the national and/or catchment scale are good input data for hydrodynamic models. In Germany and its relevant catchments, these input data are publicly available on https://ws-klimaportal.bafg.de, while for Switzerland, the hydrological projections for all catchments are available from National Center for Climate Services (https://www.nccs.admin.ch/nccs/en/home.html).

Presently available predictions suggest a strong reduction of discharges in the River Rhine especially in summer (Fig. 3 left). After the year 2050, discharges and thereby water levels will substantially drop during the vegetation period. The summer of 2018 was a first glimpse of future hydrological conditions in the River Rhine with a mean water level in the vegetation period (01.04. – 30.09.) of 80 cm lower than in the hydrological reference period between 1971 and 2000. The stage hydrograph of 2018 (Fig. 3 right, bold line) shows patterns which are similar to hydrographs in sub-Mediterranean climate with high discharge in winter and increasingly lower discharge during the vegetation period in summer. Assuming such a situation becoming “normal” in a future climate (representing a regime shift), it would most likely result in a change of the availability and area of habitats for floodplain organisms (Mosner et al. 2015; Bundesamt für Umwelt 2021)

Therefore, we modelled long-term floodplain inundation (mean of the annual inundations of the hydrological reference period 1970–2000) and the annual flood duration of the year 2018 using the R function “hydflood::flood3()” (Weber 2022; Weber et al. 2023) and used the resulting inundation data (days per year = da^{-1}) as input parameter for a vegetation model. Assigning the potential habitat of the White Willow (*Salix alba* L.) to a zone of typical inundations of 50 to 150 da^{-1}, the spatial shift of this potential habitat to lower lying areas could be demonstrated. In the study area (Rhine km 580 to 581), it resulted in a net area loss of 11% of the inferred habitat of the species (Figs 4, 5). Depending on the inclination of the bank area, the shift can result either in a loss or in a gain in habitat area. These results are consistent with the findings of a decrease in habitat area based on an ecological model without hydrological parameters for the same plant communities (Fink and Scheidegger 2021).

According to the European Habitats Directive, such riverine willow stands are considered to be very valuable for nature conservation, if they are of good status and growing on sites with typical environmental conditions, i.e. being

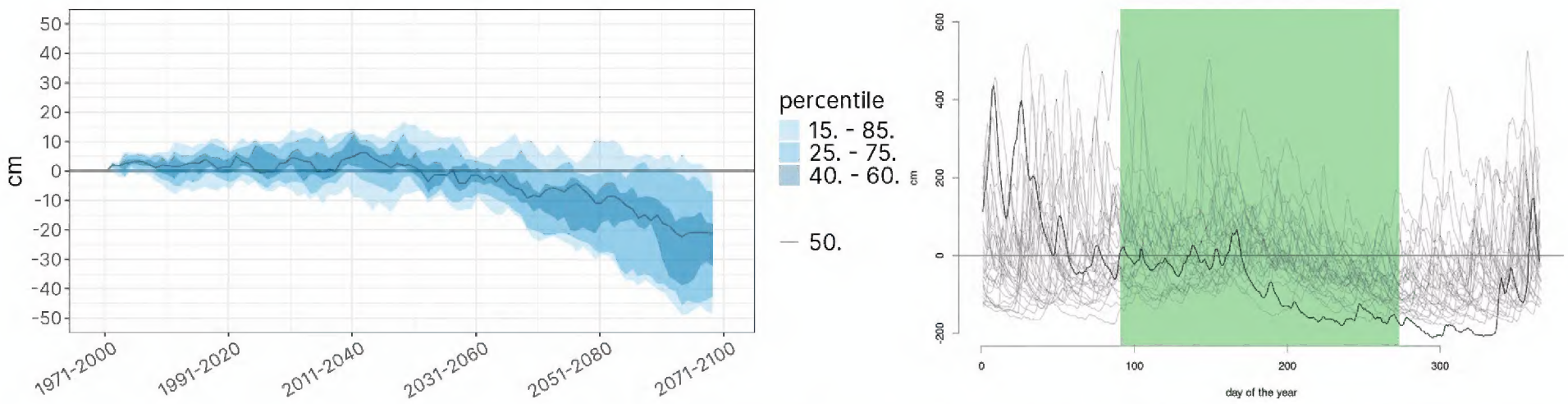

Figure 3. Gauging station Kaub (Rhine km 546.30). Left: Indicator "mean water level" (April – September) shown for moving 30-year periods between 1970 and 2100. Values are projected by the water balance model LARSIM-ME based on 16 runs (ensemble members) of the BfG Ensemble (water balance) under the assumption of the scenario RCP 8.5. Percentiles of the Ensemble (from the outside in): 15th/85th, 25th/75th, 40th/60th, 50th (black line). Source: Bundesanstalt für Gewässerkunde, das-basisdienst@bafg.de.2024. Right: Water level data (grey lines: hydrological years 2008–2017) of the gauging station Kaub (Rhine km 546.30) compared to the data for 2018 (bold line). Source: Wasserstraßen- und Schifffahrtsverwaltung des Bundes (WSV). Horizontal lines: respective median and minimal (dashed lines) water levels of the vegetation period (01.04 to 30.09.).

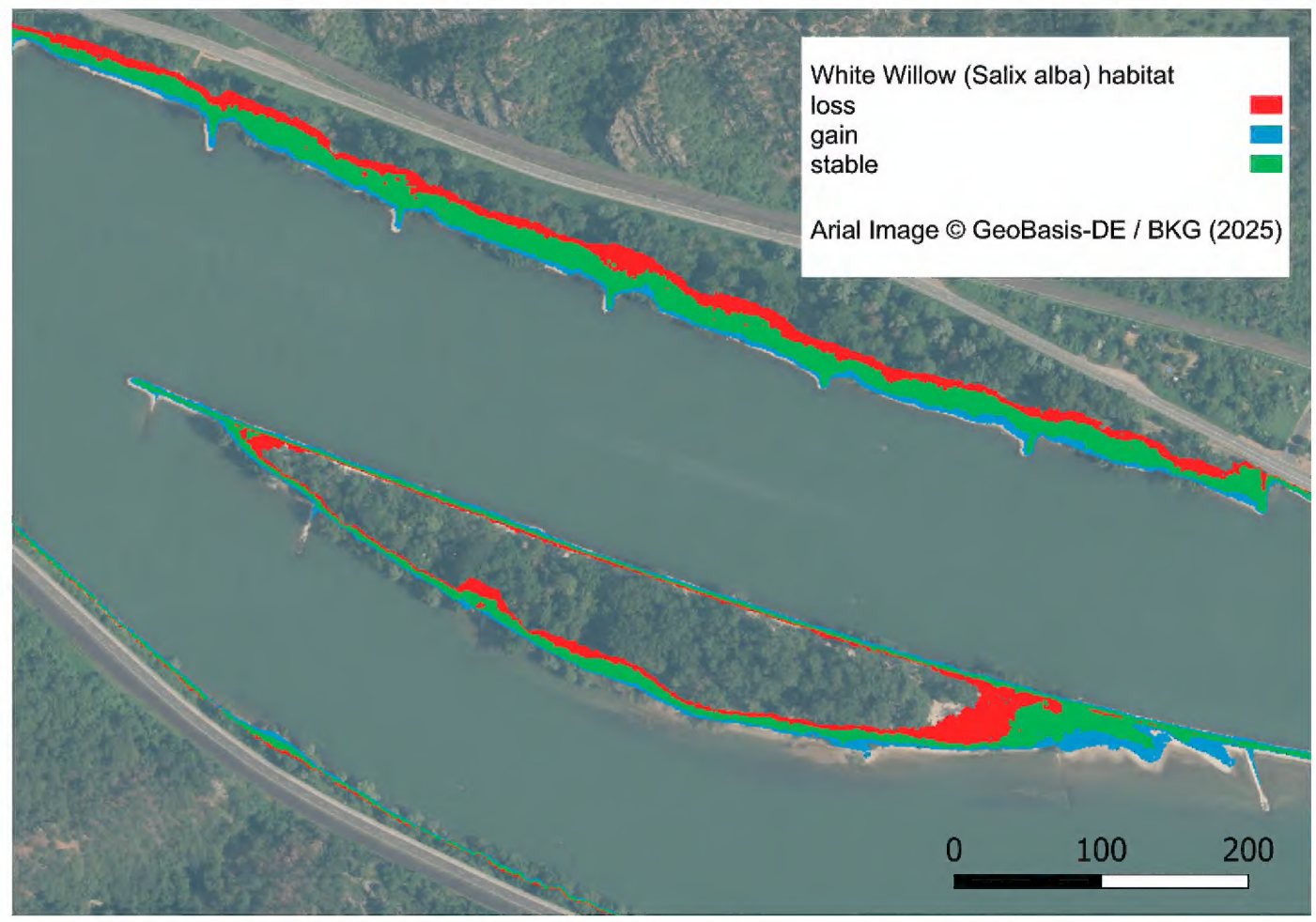

Figure 4. Visualisation of losses, gains and stable areas of the habitat potential for the tree species White Willow (*Salix alba*) in the river stretch of the middle Rhine km 580 to 581. Source of aerial photo: GeoBasis-DE / BKG (2021).

frequently flooded for long periods. Hence, such alluvial forests have been assigned the status of "priority habitat type" in the European Union (Annex I habitat type, code 91E0*). A loss of this habitat is seen as a severe impairment. Therefore, conservation action is needed to improve the situation by increasing the current realised habitat area and filling up the gaps in the fragmented riverine habitat network system, for example, by halting the removal of willow stands or by planting new ones.

For species conservation in dynamic floodplain habitats close to the river, the ecological conditions should be favourable for natural reproduction of sessile species, in order to maintain their genetic diversity and to ensure survival by, for

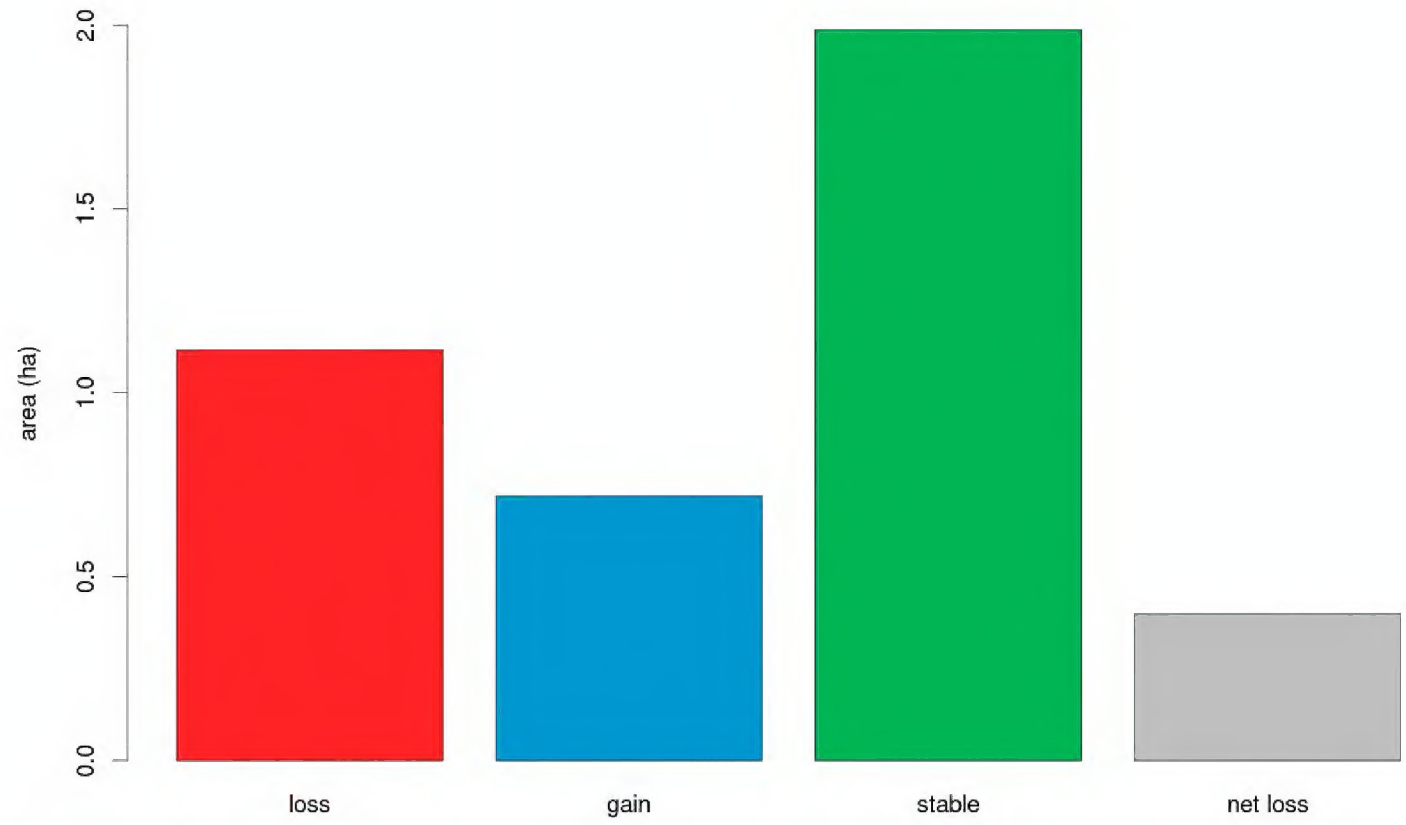

Figure 5. Balance of losses and gains in area suitable as potential habitat for the tree species White Willow (*Salix alba*) in the stretch of the river Rhine, km 580 to 581 (same as area Fig. 4).

example, fungal spore or plant seed recruitment (Sarneel et al. 2016). Therefore, patch scale hydrodynamic models linked to catchment scale species distribution models have proven to be effective in projecting habitat availability for vulnerable plant stages, such as seed establishment for pioneer plant species (for *Myricaria germanica*, see in van Rooijen et al. 2023). Local scale hydrodynamic factors inferred from hydrodynamic models might lead to more precise model predictions (Nylén et al. 2019), but are usually modelled at the patch scale for higher precision. Modelling these locally highly variable environmental factors, based on climate and following hydrological forecasts for the future, is challenging since uncertainty increases along this complex modelling chain.

Protected floodplain area: Auenschutzpark Aargau, a case study

The reported studies, based on model approaches, show that there is a high need for novel floodplain areas to be protected and that a network of habitats for conservation planning should be built to ensure resilience to a changing climate. Data on success rates for species conservation in currently protected areas over decades are rare, as monitoring programmes have only been developed recently. Here, we report on an important case study for Switzerland for a floodplain area which was protected 30 years ago in the Canton of Aargau, for which data before and after the protection and floodplain restoration have been recorded.

The landscape of the Canton of Aargau (1400 km^2) is characterised by the foothills of the Jura mountains and flat, wide river valleys. Almost two thirds of the total volume of water leaving Switzerland flows through the canton of Aargau in the Rhine at Kaiseraugst. Across Switzerland, around 71% of alluvial areas have disappeared since 1833 (Müller-Wenk et al. 2003). Historical maps show that, before the start of the floodplain conservation park programme in 1994, 88% of the original floodplain areas in Aargau had disappeared (Schelbert 2015). The dramatic decline in habitat has caused major loss of populations of many species.

The situation prompted nature conservation activists in the Aargau to launch the constitutional initiative “Auen-Schutzpark - für eine bedrohte Lebensgemeinschaft” (Floodplain conservation park - for an endangered community) in the early 1990s. This was the first initiative in Aargau to be supported by both the cantonal government and the parliament and was ultimately approved by the voters in 1993 with 67.7%. Aargau is the only canton in Switzerland with a mandate for floodplain protection inscribed in the cantonal constitution. The aim is to create a floodplain conservation park on at least 1% of the canton’s area within 20 years.

Today, 30 years later, the Aargau floodplain conservation park (“Auenschutzpark”) has been established with alluvial zones qualitatively described as ecologically “good floodplains” (Fig. 6). The task now is to secure and optimise the quality of the floodplains in the long term. As the required river dynamics are missing given the regulated discharge and embankments, the maintenance of the floodplains is a permanent task, requiring human intervention such as gravel fillings into the river to revive the river’s sluggish gravel conveyor belt or watercourse management.

Additionally, the increasing pressure of recreational use requires targeted management in order to protect natural core areas that are susceptible to disturbance. An established monitoring shows the effective changes of animal and plant populations in the restored habitats, allowing comparisons with the desired target state and recognising development trends at an early stage.

The floodplain conservation park with its diverse and comparatively large wetlands is particularly important for amphibians in the canton of Aargau. Monitoring data showed that the number of tree frogs has increased by 250% between 1999 and 2018, as well as the yellow-bellied toad (*Bombina variegata*, 50%) and the water frog (*Pelophylax lessonae*, 40%). Still, a decline was recorded for the rare natterjack toad (*Epidalea calamita*). A more restricted study in the two smaller floodplain areas (Villnacher Schachen and Bünzaue), revealed an astonishing number of 120 ground beetle species, which are indicator species for floodplains. Both results highlight the importance of protected areas in nature conservation, although securing land remains a major challenge. A new popular initiative asks for 1000 hectares of new wetlands to be created over the next 20 years has been slightly adapted by the parliament of the Canton Aargau. As an interim goal, a total of 750 hectares will be re-wetted by 2040: 300 ha in forests; 280 ha in agricultural and 170 ha in urban areas.

Figure 6. Auenschutzpark Rietheim before (left) and after (right) restoration. Photo: © Oekovision GmbH, Widen.

Conservation planning: linking catchment, reach and patch scale

Conservation planning for floodplain ecosystems in practice often starts with evaluating the adequacy of the network of protected habitats and studies at the patch size for indicator and flagship species. Species distribution models, focusing on specialised floodplain species of various organism groups, provide additional information for planning, as they re-focus on a regional or national scale instead of the patch scale, allowing to profit from networks between and amongst floodplain ecosystems (Fremier et al. 2015; Grahama et al. 2019). Additionally, data on many species can be combined and even modelled in joint species distribution models (Gavin et al. 2014; Pollock et al. 2014) and the predicted competition from invasive species can be mapped (Ikeda et al. 2014).

For successful species conservation and habitat restoration at the catchment scale, species distribution models support strategic planning for species which are only seasonably visible like fungi with fruiting bodies appearing in wet seasons mainly. Contrary to that, ecosystem restoration and management is done at the reach or patch scale and, in order to restore a whole catchment, the measures have to be done step-by-step (for example, reach-by-reach or one process at a time) over long-time periods and with high uncertainty of outcomes (Darby and Sear 2008). Therefore, the planning using species distribution models at the catchment scale and linking them to hydrological models at the reach or patch scale can help to prioritise suitable area for restoration and refugia for long-term effects on species conservation (Grahama et al. 2019; Stoffers et al. 2026). While riverine areas are often considered to be potential climate refugia due to their temperature mitigation characteristics (Zhang et al. 2023), past and ongoing stressors have already reduced the quality of many floodplain habitats (Nakamura 2022). The conservation of current floodplain ecosystems, the identification of suitable future sites for conservation and restoration and, thereafter, implementation of new protected areas for all organisms with a functional network between sites is therefore crucial, making ecological niche models useful tools for nature conservation under changing climate, especially as dynamic planning at catchment scale is required.

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Additional information

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The authors have declared that no competing interests exist.

Ethical statement

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Use of AI

No use of AI was reported.

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Author contributions

All authors planned the article. S. Fink wrote a first draft of the article with text passages provided by S. Stofer (species data and databases), A. Weber and P.J. Horchler (hydrological models and case study Rhine, including figures) and N. Kräuchi (case study floodplain Aargau including figures). All authors revised the versions of the article.

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Data availability

All of the data that support the findings of this study are available in the main text.

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